Modelling and Assessment of Soil Carbon Variability at the Point and Hillslope Scale

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EXTENDED ABSTRACT

Carbon transported throughout the catchment exists in two forms, organic and inorganic, which have different origins. The inorganic forms result primarily from the weathering of rock, whereas the organic forms result from the breakdown of biomass. Organic carbon inputs to any ecosystem consist mostly of assimilation of CO_2 (primary production) via photosynthesis. Carbon outputs from the same system include respiration by vegetation, decomposition of organic matter (e.g. leaf litter) caused by micro-organism activity, removal of biomass due to agricultural activities (harvest or land clearing), and surface and subsurface hydrologic transport of carbon.

Increases in the concentration of atmospheric greenhouse gases, principal amongst them CO_2, are a leading factor in climate change. Currently it is estimated that terrestrial carbon fluxes account for more than half of the carbon transferred between the atmosphere and the earth's surface. Unfortunately, while terrestrial ecosystems represent a critical element of the carbon interchange system, a lack of understanding of the carbon cycle at regional and sub-regional scales means that they represent a major source of uncertainty in the overall carbon budget.

It is widely accepted that our knowledge of carbon dynamics, although improving rapidly, is still insufficient to enable reliable modelling of the interplay between the carbon cycle, climate change and land use modification. On a catchment scale this entails developing an understanding of fundamental mechanisms involved in carbon, nutrient and sediment transfer throughout the catchment landscape.

Position in the landscape in relationship to hillslope curvature or slope segment has been considered an important factor in soil carbon variability (Gregorich *et al*., 1998). Hillslope position affects soil moisture content (Bevan and Kirkby, 1979), soil temperature, whether the soil is erosional or depositional and consequently plant growth type and biomass. Consequently hillslope position and soil toposequence is likely to influence soil carbon and its cycling.

There appears to be a dearth of studies examining soil carbon at the hillslope and catchment scale. It is important that hillslope processes be understood if we are to model carbon dynamics at the catchment scale (Polyakov and Lal, 2004). Digital elevation models (DEMs) have also become popular tools for quantifying and assessing catchment processes. The aim of the study is to develop an understanding of soil carbon and our ability to model it on the hillslope and catchment scale. As well as soil carbon and nitrogen concentration, soil erosion and deposition (quantified by both field data and modelling) together with soil textural properties will be examined. The ability of DEMs to capture trends in soil C and N concentrations is also assessed.

Results demonstrate that there is little change in soil C concentration down the transects over a 4 year study period for a study catchment in Arnhem Land, Northern Territory. There is also little relationship between hillslope position and C concentration and soil erosion or wetness indices when using a 10m digital elevation model. Yet significant relationships were found when using higher resolution surveyed hillslope data.

The results of this study indicate that soil C and N concentrations at the hillslope and catchment scale can be estimated using high resolution digital elevation models. Consequently, the coupling of high resolution remote sensing with catchment scale soil moisture data with a high resolution digital elevation model may enhance the ability to spatially and temporally predict soil C concentrations.

1. INTRODUCTION

Catchment carbon dynamics is linked to nutrient cycling and sediment transport and therefore will show temporal and spatial variability (Polyakov and Lal, 2004). For example, the availability of nutrients such as nitrogen has a large impact on the breakdown of organic matter because soil bacteria require nitrogen for the breakdown of plant litter and soil temperature impacts on the rate of soil biological activity. Nutrients such as phosphorus are attached to sediments and can be transported through and out of the catchment by fluvial processes. Living plant matter and leaf litter will also impact on sediment transport by providing a protective cover from rainfall and wash processes (Polyakov and Lal, 2004). Consequently to understand carbon dynamics it is essential to quantify both the spatial and temporal variation in nutrient and sediment dynamics.

Position in the landscape in relationship to hillslope curvature or slope segment has been considered an important factor in soil carbon variability (Pennock *et al*., 1994; Gregorich *et al*., 1998). Hillslope position affects soil moisture content (Bevan and Kirkby, 1979), soil temperature, whether the soil is erosional or depositional and consequently plant growth type and biomass. Consequently hillslope position and soil toposequence is likely to influence soil carbon and its cycling.

Hillslope and catchment soil erosion is also likely to affect soil carbon content. Loss of carbon is usually estimated in relation to soil loss (Gregorich *et al*., 1998; Polyakov and Lal, 2004). Erosion can redistribute soil and therefore organic carbon downslope. Natural drainage of slopes provides relatively dry hillslope divides with more moist foot slopes (Jenny, 1980). This increase in soil moisture and deposition of material from upslope provides a thicker soil profile with potentially higher soil carbon.

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2. STUDY SITES

Tin Camp Creek is in Arnhem Land, Northern Territory, Australia (Figure 1). The site is located in the seasonally wet/dry tropical environment of northern Australia, with an annual average rainfall of approximately 1400 mm, mostly falling in the wet season months from October to April. Short, high intensity storms are common and as a result fluvial erosion is the primary erosion process (Saynor *et al*., 2004).

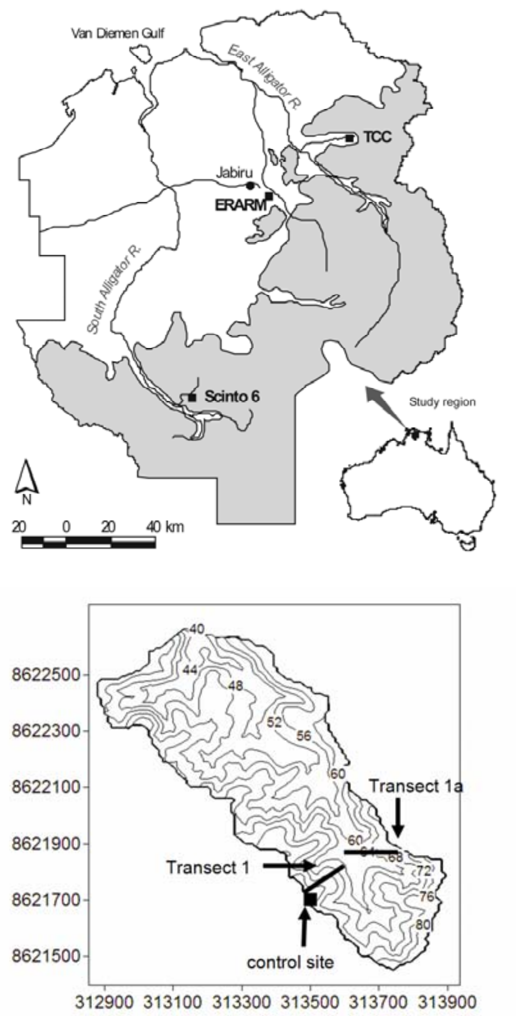

Figure 1. Location of Tin Camp Creek (TCC) study site (top) and contour plot of the study catchment (bottom).

The area is presently tectonically inactive. Tin Camp Creek is part of the Ararat Land System (Story *et al*., 1976). In this study a smaller geologically uniform 50 hectare catchment was selected for study. This catchment is representative of many others in the area and is of sufficient size to be a useful study site. The catchment consists of closely dissected short, steep slopes 10-100m long and gradients generally between 15-50%. The soils are red loamy earths and shallow gravely loam with some micaceous silty yellow earths and minor solodic soils on alluvial flats.

The native vegetation is open dry-sclerophyll forests and, although composed of a mixture of species, is dominated by *Eucalyptus* and *Acacia* species (Story *et al*., 1976). *Melaleuca* spp. and *Pandanus spiralus* are also found in the low-lying riparian areas with an understorey dominated by *Heteropogon contortus* and *Sorghum* spp. There is vigorous growth of annual grasses during the early stages of the wet season. Cover afforded by vegetation is often reduced by fire during the dry season, which enhances the potential for fluvial erosion (Saynor *et al*., 2004). In recent years the study catchment has been burnt in alternate years (Table 2).

A high quality digital elevation model of the area exists and has been described previously (Hancock *et al*., 2002). For this study a 10m by 10m grid was used to assess the relationship of soil C with catchment properties.

3. MONITORING DATA

Recent studies have demonstrated the importance of landscape position in relationship to the flow of water, sediment and organic carbon down a hillslope (Pennock et al., 1994; Gregorich et al., 1998). Consequently this approach was used to examine soil carbon at Tin Camp Creek. In this study a number of soil cores were collected for analysis both at the hillslope and catchment scale. Soil erosion and deposition and its relationship with soil carbon was also examined through the use of 137-Caesium and erosion pins.

3.1 Hillslope transects

Two hillslope transects (named Transect 1 and Transect 1a) were selected that ran from the hillslope divide to the main drainage line. The transects were opposite each other (Figure 1) and located in the middle of the catchment and were representative of the overall catchment with few trees present. Soil samples were collected in May 2002, and repeated in September 2004 and September 2005 along the same two transects, with sample points placed approximately 1 m away from each other to avoid soils disturbed by sampling in previous years. In 2005 a further series of samples were collected at 100m by 100m spacings to assess soil carbon at the catchment scale.

The length of each hillslope was measured and sampling sites selected so that samples were collected at approximately equal intervals down the slope, thus ensuring that the entire toposequence was sampled. This resulted in 16 samples being collected at 9m intervals for the 130 m long Transect 1, and 17 samples at 6 m intervals for 96 m long Transect 1a. The samples were obtained using 200mm long steel cores. In 2002 cores with an internal diameter of 86 mm were used while in 2004 and 2005 cores with a 65 mm internal diameter were used.

Soil carbon and nitrogen was also measured at depth down the soil profile. Soil cores at the hillslope divide, midslope and the toe of the slope were collected from both transects using the 65mm diameter core down to a depth of 280mm. These cores were sectioned at 40mm increments with samples dried and analysed using the same procedures employed for the other samples.

To quantitatively assess the relationship between soil carbon and vegetation in September 2005 a series of vegetation quadrats were collected down the two hillslope transects and on the 100m by 100m grid across the catchment. In all 54 vegetation quadrats and soil cores were obtained. All samples were collected away from trees in open grassed areas and were representative of the surrounding area.

3.2 Laboratory analysis

Upon collection soil samples were removed from the steel cores and were immediately air dried in an oven at 40°C for 2-3 days. The dried samples were gently disaggregated and mixed with a mortar and pestle. The sample was then passed through a 2 mm sieve and the coarse fraction (> 2 mm) separated. The < 2 mm fraction was further disaggregated with a mortar and pestle, mixed and weighed.

Soil cores were analysed for their textural properties (%sand, %silt, %clay) using the hydrometer method (Geeves *et al*., 2000). The <2mm fraction of soil was ground in a mill and a LECO 2000 analyser used to determine soil C and N content.

3.3 Soil erosion and deposition

Several studies have examined the relationship between soil carbon, soil nitrogen and soil erosion (Palis et al, 1997; VandenBygaart, 2001; Polyakov and Lal, 2004). The Tin Camp Creek catchment is located in an area with an extremely high erosivity index and fluvial erosion is a significant landscape process. Vegetation patterns are likely to be influenced by soil erosion and deposition. It can be expected that in areas of high erosion, soils will be shallower and have less water holding capacity and nutrients while in areas of deposition soils will be deeper with the ability to support increased vegetation biomass. In this study soil erosion and deposition was quantified by use of ^{137}Cs (Loughran, 1989) and erosion pins (VandenBygaart, 2001).

4. RESULTS

Results demonstrate that average soil organic carbon concentrations along Transects 1 and 1a did not change significantly between 2002 and 2005 (Table 1). On average soil carbon for Transect 1 was less than Transect 1a. Nevertheless there was no significant difference between transect or years. Similar results were found for soil N and the C:N ratio.

Table 1. Soil C (% by mass) for Transect 1 and 1a.

	Mean	S.D.	Min.	Max.
Transect 1				
2002	0.59	0.18	0.42	1.77
2004	0.70	0.16	0.57	1.18
2005	0.73	0.14	0.56	1.12
Transect 1a				
2002	0.70	0.30	0.55	1.58
2004	0.98	0.47	0.15	2.11
2005	0.95	0.29	0.61	1.55

Carbon concentration for each transect was plotted in relationship to its hillslope profile (Figure 2). The data for T1 follows the same trend down the hillslope profile for the 3 years of data whereas there was much more variability in the Transect 1a data. Similar results were found for soil N and C:N ratio. The soil C and N concentrations for the 1ha grid samples collected in 2005 both have higher means than the transect samples and a larger range. Nevertheless these are not significantly different to the transect data for 2005. Soil C and N concentration also showed an exponential decline with depth for the soil cores collected at the catchment divide, mid-slope and at the foot of the slope (Figure 3).

Both transects had similar soil textural properties. Textural analysis revealed that the collection of soil cores demonstrated a limited range of sand, silt and clay content with most soils being classified as either sandy loam or sandy clay loam. Transect 1a had a higher clay content on average than for Transect 1. Nevertheless the textural properties of the transects were not significantly different from each other. An analysis of soil textural properties for each transect showed no trends down each profile. Soil carbon and soil textural properties were statistically assessed but showed no strong statistical relationships. Similar results were found for soil nitrogen and C:N ratio.

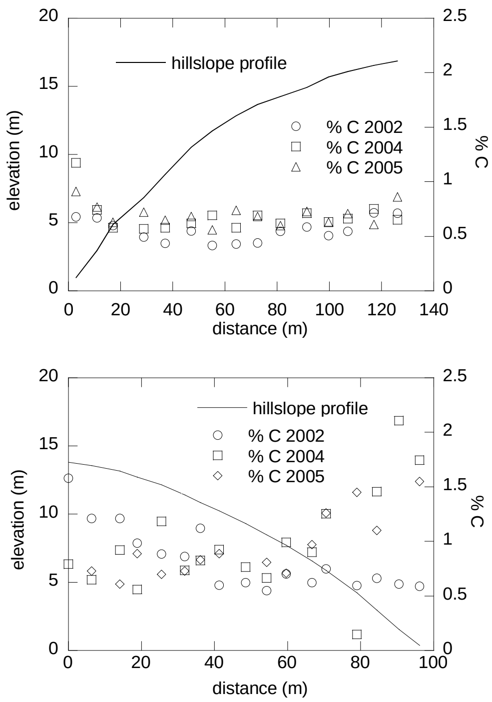

Figure 2. Hillslope profile and soil carbon for transect 1 (top) and 1a (bottom).

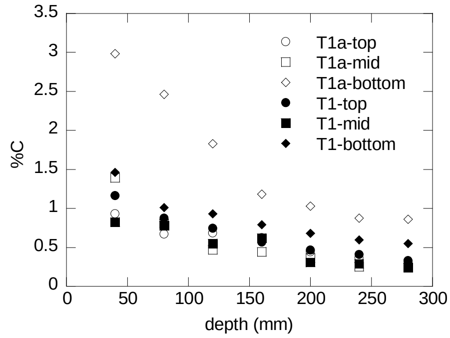

Figure 3. Soil carbon at 4cm depth increments at the top, midslope and bottom of Transect 1 and 1a.

To evaluate soil carbon content and its relationship with soil erosion each soil core was analysed for its ^{137}Cs content. A high value of ^{137}Cs in soil indicates deposition while a low value indicates erosion. In this study the relationship between soil carbon and ^{137}Cs was examined using both spatial and mass units however no relationship was found. While other authors have found relationships between soil carbon and ^{137}Cs, these studies have all been conducted on hillslopes that have been tilled for agriculture.

Results from the erosion pins display considerable variation in the erosion and deposition rates down each transect. Overall both transects were eroding with the erosion rate for Transect 1 was higher than for Transect 1a however the difference was not significant. Comparison of soil C and N concentration at each point with the erosion and deposition rates from the erosion pin data had no statistical relationship.

The soil C data was compared to hillslope geomorphic attributes such as slope and upslope contributing area together with wetness indices (Table 2). Using the 10m DEM no statistically significant result was found. Similar results were found for the samples collected on a 100m by 100m grid across the entire catchment.

Table 2. Relationship (r^2) between soil C and slope derived from a 10m DEM and surveying.

	Transect 1		Transect 1a	
	Slope (DEM)	**Slope (surv.)**	**Slope (DEM)**	**Slope (surv.)**
2002	0.01	0.67	0.30	0.76
2004	0.19	0.46	0.35	0.85
2005	0.01	0.57	0.34	0.77

5. DISCUSSION AND CONCLUSIONS

The results of this study demonstrate that there is little change in soil C concentration down the transects over the study period. Soil C and N is higher on average for Transect 1a than for Transect 1 but the transects are not significantly different and there is little difference between years. Examination of soil textural properties and C and N content demonstrates that there was in some cases weak statistical relationships but nothing that was consistent between data sets. Soil textural analysis demonstrates that clay content is higher on average for Transect 1a than for Transect 1 which may help explain the difference in average soil carbon levels observed for the two profiles.

Many studies have suggested a relationship between soil carbon and soil erosion and deposition. The relationship between soil erosion and soil C concentrations was examined using erosion pin data for a single year and ^{137}Cs data which is a measure of soil erosion and deposition over an approximately 50 year period. In this study the erosion pin data for the two transects demonstrate no relationship with soil C and N concentrations. This finding may be a result of the limited amount of erosion pin data (one year) and many more years of data is likely to be needed to resolve this issue. These pins will continue to be monitored over future years.

The data from the two transects indicates that there is no relationship between soil carbon and nitrogen and ^{137}Cs content. While the labelling of ^{137}Cs with the clay fraction has been shown to be variable (Loughran, 1994) it is reasonable to expect that a mean trend would be observed from the number of samples collected over the study period. This study calls into question the relationship between soil erosion/deposition and soil carbon in the study catchment using the ^{137}Cs method.

It should be noted however that this study site is different to all others where a statistical relationship between soil C and N concentration and ^{137}Cs content has been found. Firstly, the ^{137}Cs content is very low compared to the Northern Hemisphere where the majority of studies have been conducted. Secondly, the majority of studies that have found a relationship between soil carbon and ^{137}Cs content have been conducted in agricultural fields that have been subject to tillage leading to a likely mixing of both carbon and nitrogen throughout the profile whereas this study catchment is undisturbed by Europeans. This issue is an area for further investigation.

These findings suggest that soil carbon models which relate sediment transport to soil organic carbon (i.e. Century and EPIC) should be used with caution.

Soil C and N at each point on the transect were compared to slope, upslope contributing area and wetness indices such as TOPMODEL (Bevan and Kirkby, 1979) derived from the 10m DEM. No statistically significant relationships were found. Regridding the 10m DEM to a 5m DEM (the maximum resolution possible given the number of points and spacing of the original data) did not improve any of the relationships.

To further examine this finding the hillslope profiles for Transect 1 and 1a were surveyed using a Total Station to provide a precise measure of hillslope shape. Strong relationships were found when soil C and N was compared with slope at each point as well as distance from hillslope divide (Table 2).

Comparison of slope at each of the sample points derived from the DEM with that determined by surveying demonstrates that the DEM derived data does not capture the hillslope detail of the surveying. Subtle breaks and changes in slope over length scales of 1-2m are missed. This suggests that microtopography plays a significant role at the study site in biogeochemical cycles. While the DEM has been deemed to be good quality for catchment scale geomorphological assessment (Hancock *et al*., 2002) it has insufficient resolution for soil assessment as examined in this study.

These findings demonstrate that soil carbon is related to catchment geomorphology and hydrology for the study catchment. The results demonstrate that soil C and N concentrations at the hillslope and catchment scale can be estimated using high resolution hillslope data. Consequently, the coupling of high resolution remote sensing with catchment scale soil moisture data with a high resolution digital elevation model may enhance the ability to spatially and temporally predict soil C concentrations.

While not possible at this stage to define a suitable DEM grid size for the study catchment, the evidence here suggests that a grid less than 5m is required. Initial data from other study sites (see Rudiger et al., 2007) indicate that 5m is still too coarse and that 2m spacings or better is required for biogeochemical assessments such as this. The ground based surveying using a Total Station to determine accurate hillslope profiles is time consuming and not practical on the catchment scale. While LIDAR is currently expensive, it is the only practical method at present with the ability to capture high resolution topographic data. This issue is currently being investigated by the authors.

The results of this study demonstrate that further work is required to better understand soil carbon and nitrogen at the hillslope scale. This information is needed if we intend to not only better understand hillslope soil carbon but also carbon at the catchment scale. This knowledge is especially important if we are to numerically model landscape response to different inputs and resultant impact on soil carbon.

6. ACKNOWLEDGMENTS

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